FINAL REPORT
Cheap DECAF: Density Estimation for Cetaceans from Acoustic Fixed sensors using separate, non-linked devices

David K. Mellinger
Cooperative Institute for Marine Resources Studies
Oregon State University
2030 SE Marine Science Dr.
Newport, OR 97365
phone: (541) 867-0372 fax: (541) 867-3907 email: David.Mellinger@oregonstate.edu

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LONG-TERM GOALS

Several of the current methods for density estimation of cetaceans using passive fixed acoustics rely on large, dense arrays of cabled hydrophones and/or auxiliary information from animal tagging projects conducted at the same time as the acoustic survey. Obtaining such data is costly, and may be impractical to the wider community interested in estimating cetacean density. Therefore, the goal of Cheap DECAF is to focus on the development of cetacean density estimation methods using sensors that are sparsely distributed and less expensive to deploy than the cabled military arrays focussed on to date.

Note: This project involves components from Oregon State University (OSU) and the University of St. Andrews (grant number: N00014-11-1-0615, PI: Len Thomas); the OSU portion is the principal topic of this report, though the St. Andrews component is mentioned when relevant.

OBJECTIVES

Recordings from a sparse array of Ocean Bottom Seismometers (OBSs) equipped with hydrophones were used to develop and test a new density estimation method for fin whales (*Balaenoptera physalus*). The OBS array was deployed as part of the NEAREST project in 2007-2008 near the Strait of Gibraltar southwest of Portugal (Fig. 1).

The specific objectives of the OSU portion of the project (i.e., this grant) were (1) to develop and apply methods for density estimation based on measuring total sound energy in relevant frequency bands, and (2) to obtain baseline estimates of spatial density of fin whales in the study area.

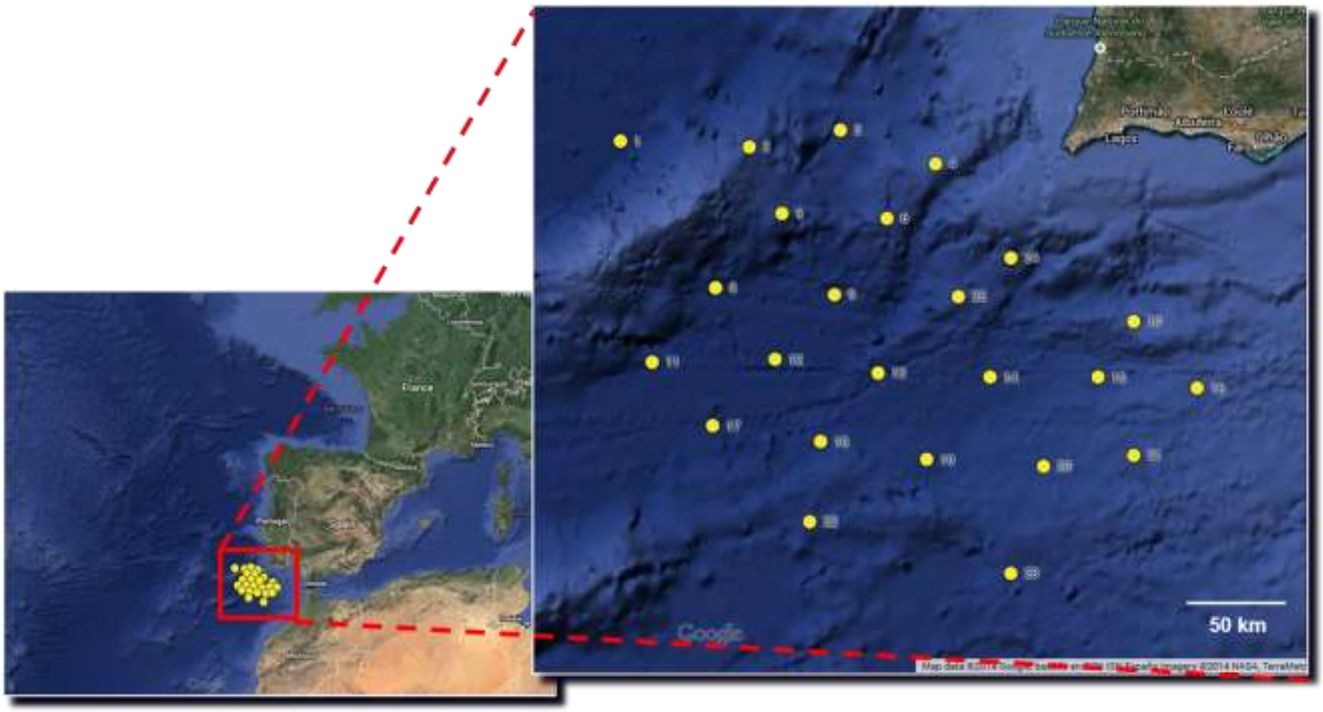


Fig. 1. Location of the array of 24 OBS sensors equipped with hydrophones that was deployed in 2007-08 in the Atlantic off Portugal. Sensor #7, which was deployed between #1 and #8, did not collect data successfully and is omitted. Map courtesy of Google, Inc.

APPROACH

The approach was to develop a method that uses the total energy present in a species' frequency band as the statistic upon which a density estimate is made. The approach used involves a Monte Carlo simulation and propagation modeling, to link density of animals to a given received energy level.

There was also a project management element in which bi-monthly teleconference progress meetings with St. Andrews were held, and two face-to-face meetings, which were held in 2012 and 2013.

WORK COMPLETED

The technical work comprised five phases:

(1) Estimation of the average duty cycle and source level of singing fin whales;
(2) Simulation of populations of singing whales at various densities in the vicinity of each hydrophone, and estimation of the corresponding received level (via acoustic propagation modeling) from their combined sound at each hydrophone;
(3) Combining this information into a function mapping simulated density to received level, and inverting this function to map received level to density;
(4) Measurement of the actual received level at each hydrophone throughout the year from fin whale vocalizations, with removal of noise sources;
(5) Application of the measurements to the RL-to-density function to estimate density, and plotting of the resultant densities throughout the year.

Phase 1 of the work was to estimate the duty cycle and source level of fin whales in the area. The calling rates of singing fin whale were estimated by measurement of the pulse periods of 13 singing whales, with a resulting mean of 13.44±0.2 s (Fig. 2). (Incidentally, this approximately matches the interval of the Mediterranean Sea population of fin whales shown by Hatch and Clark (2004), suggesting that these southwest-of-Portugal whales may be drawn from the same population.) Information on fin whale pulse sequence length, inter-sequence interval, and bout length were obtained from the literature (e.g., Watkins et al. 1987). These data were combined to estimate the *overall average pulse rate*, accounting for the various types of silent intervals, of 22.6 s.

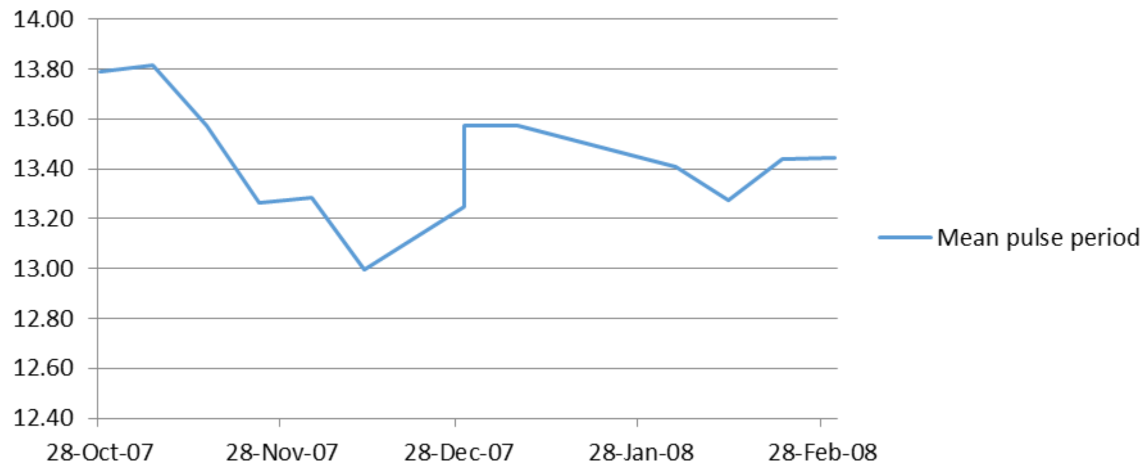


Fig. 2. Mean pulse periods of 13 fin whales throughout the year of the study. Each point on the graph represents the mean of many (9-133) measurements of a single whale's pulse period on the date indicated. Pulse periods throughout the year for pulse sequences, when a whale was calling regularly without interruption, averaged 13.4 s.

Measuring the amplitude envelope of an average fin pulse showed that the *effective pulse duration* – the duration of a pulse with the same energy as a normal fin pulse, but having constant amplitude – was 0.270 s. This, combined with the 22.6 s overall average pulse rate, gave a duty cycle of 1.23%.

A distribution of fin whale source levels was also estimated from the literature, with the most valuable distribution of source levels coming from Payne and Webb (1971). For singing whales, their mean source level of the loudest instant of each pulse was 179 dB_{RMS} re 1 µPa at 1 m. This implied that the *effective source level* of a fin whale – the level that produced the same sound power if the whale produced sound continuously instead of in pulses – was 141 dB_{RMS} re 1 µPa at 1 m.

Phase 2 involved simulating populations of fin whales at different densities around each hydrophone, and estimating how loud their sounds would be at the hydrophone – i.e., what their received level (RL) would be. This was done by first estimating the propagation loss from various radials around each hydrophone (Fig. 3) to that hydrophone using acoustic propagation modeling. Propagation modeling was done using RAM (Range-independent Acoustic Model; Collins 1994) by Portland State University student Elizabeth Küsel. Next, a Monte Carlo method was used: simulated whales at various population densities were placed randomly in the study area, and the contributions of each one to the RL at the hydrophone were estimated by using the effective source level (above) and the propagation loss from the nearest point on a calculated radial. (Locations on land within the distance of some

radials, as suggested by Fig. 3, were omitted from the simulation.) Contributions from all simulated whales were summed to achieve an overall received level for a given fin whale density.

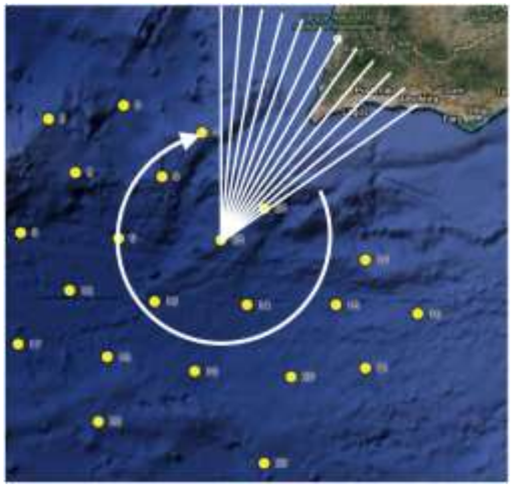


Fig. 3. Radials around a hydrophone instrument at which acoustic propagation loss was calculated. Map courtesy of Google, Inc.

In Phase 3, this process was repeated for a large number of simulated fin whale densities, resulting in the density-to-RL curve shown in Fig. 4. When the data are displayed using a log-log scale, the resulting curve is fit well by a straight line, as expected. The equation of this line is

$$RL_{fin} = 9.87 \log_{10}(\text{density}) + 135.0 \qquad (1)$$

with density in whales/1000 km^2 and other values in dB re 1 µPa.

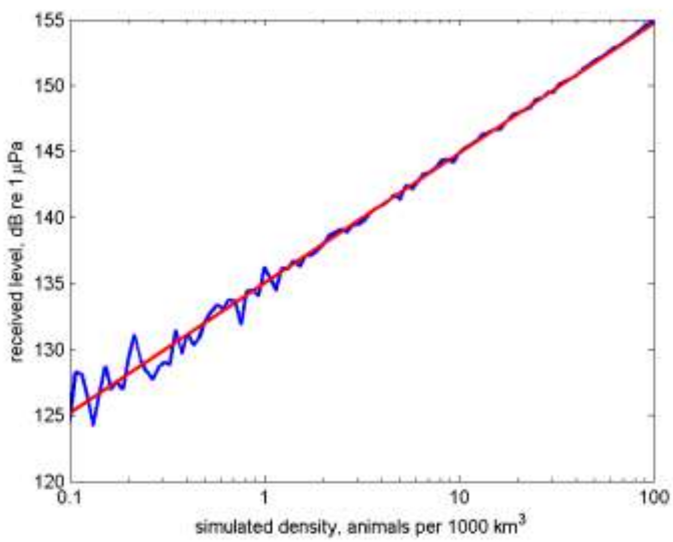


Fig. 4. The output of the Monte Carlo model: the blue curve shows modeled received level (RL_{fin}) as a function of simulated density for one hydrophone location, with red showing the least-squares best-fit line. This function was inverted to allow converting measured RL_{fin} values to densities.

The inverse of this function – or more accurately, of the line fit to it – is the desired RL_{fin}-to-density function:

$$\text{density} = 10^{((RL_{fin} - 135.0) / 9.87)} \quad (2)$$

with the same units as Eq. (1).

Phase 4 was to measure the received energy of sound from fin whale vocalizations. This involved measuring the total energy in the whales' frequency band and, to improve this estimate, reducing or removing unwanted components (i.e., noise) present in this band. Noise reduction methods were based on successive linearly-scaled power spectra – a "power spectrogram." To effect noise reduction, two types of conditioning (Mellinger 2013) were applied to each spectrum, corresponding to two principal varieties of noise:

(1) *Reduction of narrowband noise* – spikes in the power spectrum -- which typically came from ships and other mechanical noise sources. This noise was lessened by removing the spikes using a median filter – a filter that, for each frequency f in the spectrum, examines the neighborhood $[f - \Delta f, f + \Delta f]$ about f and replaces the spectrum value at f with the median of the values in the neighborhood. Choice of the filter half-width Δf is critical: it must be large enough to span at least twice the width of spectral lines from ship sounds (so that the median in the neighborhood represents non-ship sound rather than the ship sound), but small enough to not remove or significantly alter spectral peaks from fin whale sounds. A variety of values were applied to a sample of ship sounds, and a value of $\Delta f = 1.5$ Hz was found to work well.

(2) *Reduction of broadband noise*, whether impulsive or relatively stationary, which came from seismic airguns (impulsive) and wind/waves (stationary). The approach taken was that sound power in the fin whale band (after median filtering) is the sum of broadband noise and fin whale sound:

$$RL_{total} = RL_{noise} + RL_{fin} \quad (3)$$

The noise power level across the fin whale band was estimated by measuring the spectrum level at two frequencies flanking (below and above) the target frequency band, then interpolating between them to estimate the noise power (RL_{noise}) in the fin whale band. From Eq. (3), this power could then be subracted from the total power in this band (RL_{total}) to achieve an estimate of the portion of the power due to fin whales (RL_{fin}). Fig. 5 illustrates the estimation of the broadband noise power level.

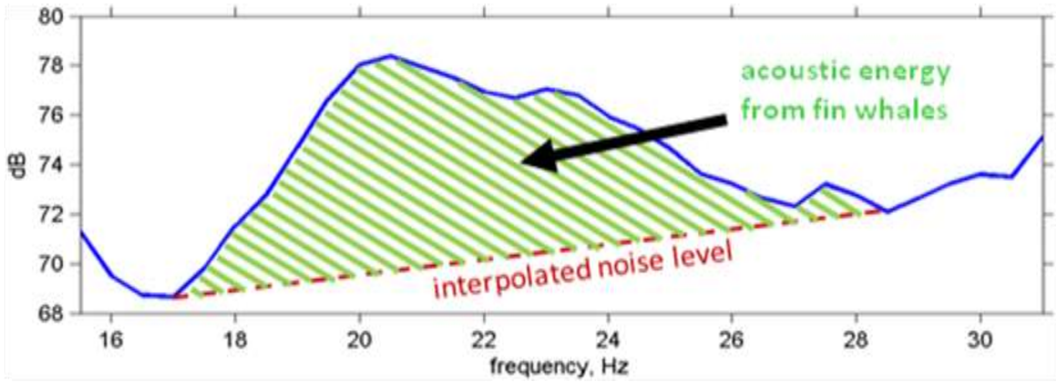


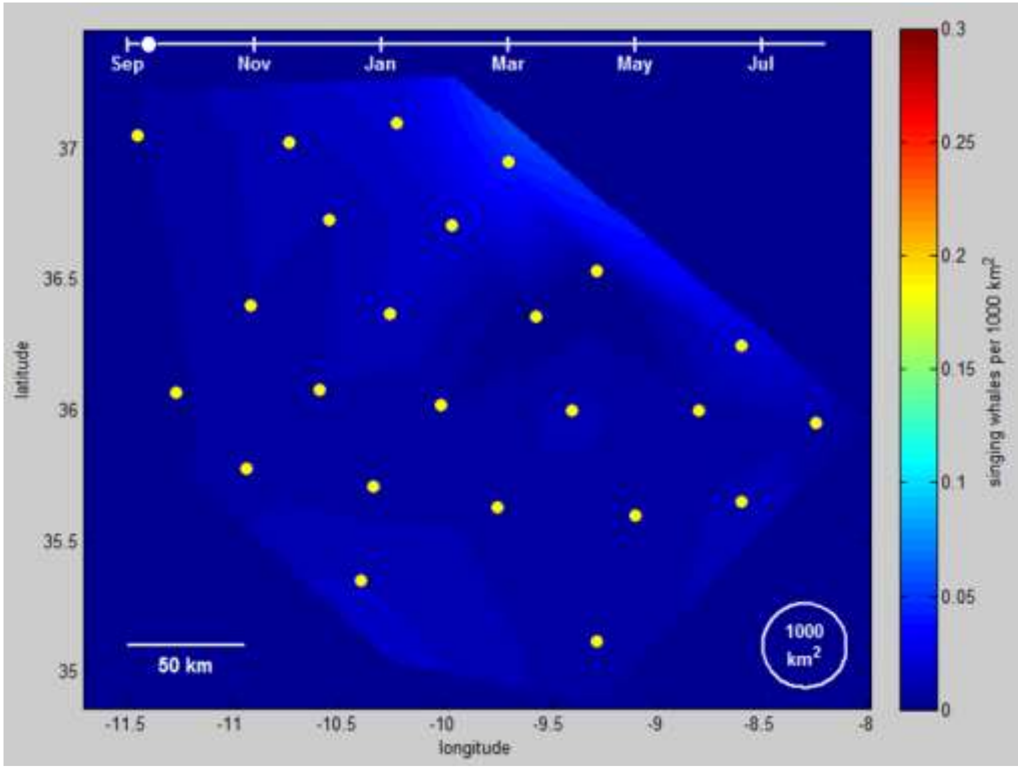
Fig. 5. A spectrum containing the fin whale energy band (17-27 Hz) showing how interpolation is done to estimate the background noise level. This step is done after the reduction of narrowband noise described above.

Once these noise sources were removed, the received level from all the combined fin whale vocalizations was measured at each hydrophone over the course of the year-long deployment on the 24 instruments. Completing this required substantial computation.

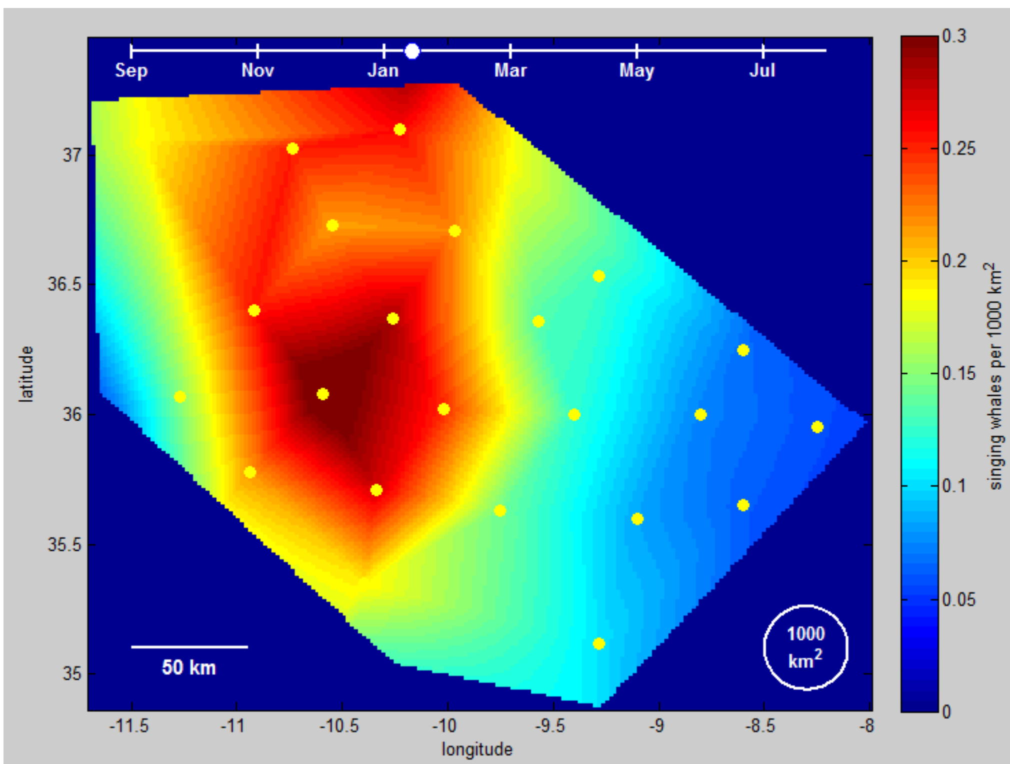
Phase 5, the final step, was applying the measured RL_{fin} values from each hydrophone over the course of the year to Eq. (2) and plotting the resulting fin whale densities throughout the year. To prevent a single loud whale near a hydrophone from resulting in an incorrectly large density estimate, RL_{fin} estimates were averaged over 5-day intervals. This was repeated for all 24 hydrophones. Spatial interpolation was used to estimate fin whale density in between the hydrophone locations, and the result plotted as a density image. This was repeated every 5 days throughout the year, and a video was produced showing fin whale density over the course of the year.

RESULTS

Fin whale density was estimated across the area of the hydrophone array over the course of the year and a video was produced. This video, and the methods described above used to make the video, were presented at the fall 2014 meeting of the Acoustical Society of America (Mellinger et al. 2014) and at the 2015 conference on Detection, Classification, Localization, and Density Estimation (DCLDE) of Marine Mammals using Passive Acoustics (Mellinger et al. 2015). Figure 6 shows frames from this video.



(a)



(b)

Fig. 6. Frames from (a) Sept. 2007 and (b) Jan. 2008 from a video showing singing fin whale density throughout the year for the study location off Portugal. Color indicates whale density, with calibration scale at right; yellow spots are hydrophone locations; timeline at top indicates the time of year; circle at lower right is 1000 km^2, the area used in the unit of whale density (singing whales per

1000 km^2). There are fewer than 24 hydrophones in (b), and in some other frames in the video (not shown here), because some hydrophones did not record for the whole year.

A paper about this work is in preparation for submission to J. Acoust. Soc. Am.

IMPACT/APPLICATIONS

The main aim of Cheap DECAF is to make density estimation of cetaceans less costly and, therefore, more accessible to the wider scientific commuity. The methods developed here will be applicable to re-deployable arrays of both sea-bed mounted instruments (such as the OBS array) and surface buoys, and so should increase our capability to monitor cetacean density in geographic areas of interest, including those where naval operations are conducted. Since there have been a large number of OBS array deployments, it is our hope that this method can be applied widely to better understand the distribution, seasonality, and population density of this endangered species.

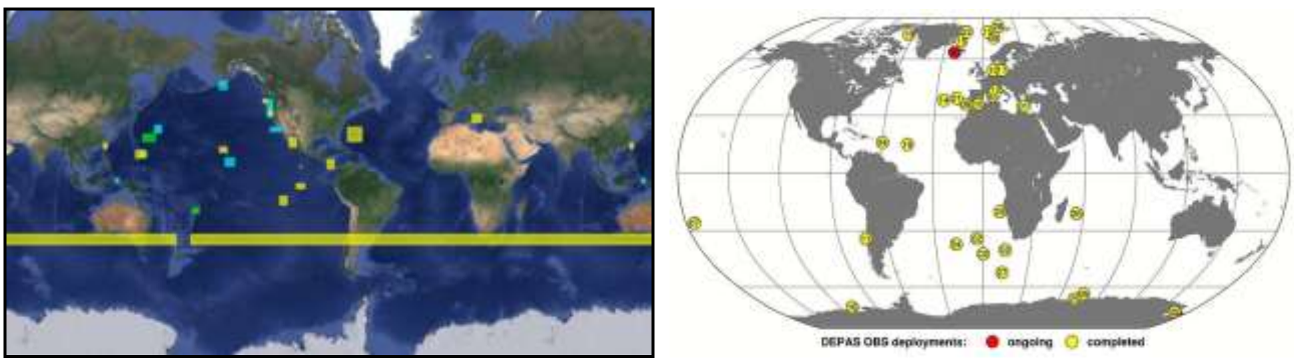


Fig. 7. Some of the OBS array deployments made worldwide to which the method developed here could be applied. (a) From the Incorporated Research Institutions for Seismology (IRIS). (b) From the Alfred Wegener Institute (AWI), Germany.

RELATED PROJECTS

Cheap DECAF (grant number: N00014-11-1-0615, PI: Len Thomas, University of St. Andrews).

An investigation of fin and blue whales in the NE Pacific Ocean using data from Cascadia Initiative ocean bottom seismometers (grant number: N00014-14-1-0423; PI: William Wilcock, University of Washington).

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PUBLICATIONS

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